Cherenkov gluons at RHIC and LHC

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Abstract

The coherent hadron production analogous to Cherenkov radiation of photons gives rise to the ring-like events. Being projected on the ring diameter they produce the two-bump structure recently observed for the away-side jets at RHIC. The position of the peaks and their height determine such properties of the hadronic medium as its nuclear index of refraction, the parton density, the free path length and the energy loss of Cherenkov gluons. Beside comparatively low energy gluons observed at RHIC, there could be high energy gluons at LHC, related to the high energy region of positive real part of the forward scattering amplitude and possessing different characteristics.

Analogous to Cherenkov photons, the Cherenkov gluons [1, 2, 3, 4, 5] can be emitted in hadronic collisions provided the nuclear index of refraction n exceeds 1. The partons moving in such nuclear medium would emit them. These gluons should be emitted at the cone surface with the cone angle θ in the **rest system** of the **infinite** medium defined by the relation

$$\cos\theta = \frac{1}{\beta n}, \tag{1}$$

where β is the ratio of the velocities of the parton-emitter and light which can be replaced by 1 for relativistic partons.

Prediction 1. According to Eq. (1) the ring-like two-dimensional distribution of particles must be observed in the plane perpendicular to the momentum of the parton-emitter.

Proposal 1. Plot the one-dimensional pseudorapidity ($\eta = -\ln\tan\theta/2$) distribution with trigger momentum as z-axis neglecting the mismatch of trigger and away-side jets directions. It should have maximum at (1).

This plot is still unavailable at RHIC. RHIC experiments [6, 7] have shown the two-bump structure of the azimuthal angle distribution (now with z-axis chosen along the collision axis) near the away-side jets. It results due to the one-dimensional projection of the ring on the azimuthal plane. Ring's plane is perpendicular both to the trigger momentum and to the plane in which momenta of colliding particles and trigger are placed. It is clear that projection of a ring on its diameter in the azimuthal plane is not the best one to reveal its properties. The proposal 1 uses better (circular) projection of the ring. The shapes of two- and three-particle correlations studied at RHIC [8, 9] are its less direct indications although they have the ring-like structure themselves.

From the distance between the peaks defined in angular ($\theta = D$ in PHENIX notation) variables one gets according to Eq. (1) the nuclear index of refraction. Its value is found to be quite large $n = 3$ compared to usual electromagnetic values close to 1. If interpreted in terms of the Breit-Wigner resonances, as explained below, it results in the large density of partons in the created quark-gluon system with about 20 partons within the volume of a single nucleon [10]. It agrees with its estimates from v_2 and hydrodynamics. This value is also related to the energy loss of gluons estimated in [10] as $dE/dx \approx 1$ GeV/Fm. The height of the peaks determines the width of the ring which in its turn defines the free path length of Cherenkov gluons [10] which happens to be long enough $R_f \sim 7$ Fm. Thus they hadronize, probably, close to the surface of the initial volume.

These estimates were obtained [10] using the relation of the index of refraction to the forward scattering amplitude [11]

$$\mathrm{Re}n(E) = 1 + \Delta n_R = 1 + \frac{6m_\pi^3\nu}{E^2}\mathrm{Re}F(E) = 1 + \frac{3m_\pi^3\nu}{4\pi E}\sigma(E)\rho(E). \quad (2)$$

Here E denotes the energy, ν is the number of scatterers within a single nucleon, m_π the pion mass, $\sigma(E)$ the cross section and $\rho(E)$ the ratio of real to imaginary parts of the forward scattering amplitude $F(E)$. Thus the emission of Cherenkov gluons is possible only for processes with positive $\mathrm{Re}F(E)$ or $\rho(E)$. It is well known that this requirement is fulfilled within one of the wings of any Breit-Wigner resonance[1]. Gluons with wide energy spectrum are emitted during the collision. However only those whose energy fits the corresponding wing of the resonance (e.g., ρ-meson) which they form with the thermalized (or any other) gluons of the medium during the hadronization process can satisfy the requirement $n > 1$. Inserting the Breit-Wigner shapes

[1]At the maximum of the resonance $\mathrm{Re}F(E) = 0$ as seen below in Eq. (3). In particular, this is used to solve the problem of abundance of elements in the Universe (e.g. see [12]).

in Eq. (2) one gets for a single resonance

$$\mathrm{Re}\, n(E) = 1 + \frac{2J+1}{(2s_1+1)(2s_2+1)} \frac{6m_\pi^3 \Gamma_R \nu}{E E_R^2} \frac{E_R - E}{(E-E_R)^2 + \Gamma_R^2/4}. \qquad (3)$$

Here J, s_1, s_2 are spins of the resonance and its decay products, E_R, Γ_R are its position and width. The above estimates of parton density ν follow from this expression for the nuclear index of refraction with account of all mesonic resonances (sum over R in Eq. (3)). It also predicts the unusual particle content within the ring because only energies $E < E_R$ matter to get $n > 1$.

Prediction 2. According to Eq. (3) the resonances formed within the ring have masses shifted to smaller values somewhat below $m_R - \Gamma_R/2$ with asymmetrical distribution when reconstructed from their decay products.

Proposal 2. Plot the distribution of masses of $\pi^+\pi^-$ or e^+e^--pairs in the ring.

In the ρ-meson region it will be peaked slightly below $m_\rho - \Gamma_\rho/2 = 700$ MeV if no shift is added due to the medium. The attenuation of Cherenkov gluons is moderate at these masses as can be shown from Eq. (3) (see [13]) and follows from above values of dE/dx and R_f. The e^+e^--mode is less probable but has much lower background. Particles momenta are relativistic [13].

Let us stress that we do not require ρ-mesons or other resonances pre-exist in the medium but imply that they are the modes of its excitation formed during the hadronization process of partons. The Cherenkov gluon emission is a collective response of the quark-gluon medium to impinging partons related to its hadronization properties. It is determined by the energy behavior of the second term in Eq. (3).

For the sake of simplicity, Eqs. (2) and (3) valid at small Δn_R typical for gases are used here. The value $n = 3$ corresponds to a dense liquid. Therefore, it is proper to use the formula [12]

$$\frac{n^2-1}{n^2+2} = \frac{m_\pi^3 \nu \alpha}{4\pi} = \sum_R \frac{2J_R+1}{(2s_1^R+1)(2s_2^R+1)} \cdot \frac{4m_\pi^3 \Gamma_R \nu}{E E_R^2} \cdot \frac{E_R - E}{(E-E_R)^2 + \Gamma_R^2/4}, \qquad (4)$$

where α denotes the colour polarizability of the colour-neutral medium. The value ν obtained from this expression is almost twice lower than given above. It does not change the qualitative conclusions about the dense medium (for more details see [13]). From Eq. (4) one can easily estimate that Ren is more than three times larger Imn at the maximum of the shifted resonance.

The Cherenkov gluons discussed above are comparatively low energy ones and coalesce to resonances. They originate from those regions of positive real part of the forward scattering amplitude which are bound within the left wings of the resonances. However, from dispersion relation predictions and experiments with various colliding hadrons [14, 15] we know that there exists the high energy region of hadronic reactions where the real part of the forward scattering amplitude (or $\rho(E)$) is positive for all colliding partners. It happens at energy exceeding E_{th}=70 - 100 GeV in the target rest system. Considering it as a common property of hadron reactions, we hope that high energy gluons possess the similar feature as carriers of strong forces.

Prediction 3. The very high energy forward moving partons can emit high energy Cherenkov gluons producing jets.

Proposal 3. Plot the pseudorapidity distribution of dense groups of particles in individual events (now again with collision axis chosen as z-axis) and look for maxima at angles determined by Eq. (1).

There are no gluons with such energy at RHIC but they will become available at LHC. Namely such gluons were discussed in [1, 2] in connection with the cosmic ray event at energy 10^{16} eV (in the target rest system E_t) with the ring-like structure first observed [16]. This energy just corresponds to LHC energies. The partons emitting such gluons move with high energy in the forward direction. With Re$F(E_t)$ fitted to experimental data and dispersion relation predictions at high energies one can expect (see [1, 2]) that the excess of n over 1 behaves as

$$\Delta n_R(E_t) \approx \frac{a\nu_h}{E_t}\theta(E_t - E_{th}). \tag{5}$$

Here, $a \approx 2 \cdot 10^{-3}$ GeV is a parameter of Re$F(E_t)$ obtained from experiment (with dispersion relations used) and ν_h is the parton density for high energy region. It can differ from ν used at low energies. $\Delta n_R(E_t)$ decreases with energy for constant ν_h. In this case Eq. (2) should be applicable. It would imply that the medium reminds a gas but not a liquid for very high energy gluons, i.e. it becomes more transparent.

The angles of the cone emission in c.m.s. of LHC experiments must be very large nevertheless (first estimates in [2] are 60^o - 70^o), i.e. the peaks can be seen in the pionization region at central pseudorapidities. In more detail it is discussed in [1, 2, 13, 17]. In this region the background is large, and some methods to separate the particles in the cone from the background were proposed in [17, 18].

The main difference between the trigger experiments at RHIC and this nontrigger experiment is in the treatment of the rest system of the medium. The influence of the medium motion on cone angles was considered in [19]. It is important because all the above formulas are valid for emission in the rest system of the medium.

At RHIC, the 90^o trigger jet defines the direction of the away-side jet. Because of position of the trigger perpendicular to the collision axis of initial ions, the accompanying partons (particles) feel the medium at rest on the average in the c.m.s. The similar trigger experiments are possible at LHC. It is important to measure the cone angles for different angular positions of the trigger to register the medium motion.

However, in nontrigger experiments with forward moving high energy partons inside of one of the colliding ions, the rest system of the medium is the rest system of another colliding ion. Therefore the cone angle should be calculated at that system and then transformed to the c.m.s. That is why these angles are so large even at small values of the refractivity index for high energy gluons. The low energy gluons are unobservable here because they fly backward inside the accelerator pipe (about 180^o in c.m.s.).

According to experimental data and dispersion relations predictions for hadronic reactions, there exists wide energy region below E_{th} where the real part of the forward scattering amplitudes is negative. Cherenkov gluons can not be emitted in this region. The transition gluon radiation can, nevertheless, happen. For small Δn_R it is proportional to Δn_R^2 and negligible but can become important for comparatively large Δn_R like those observed in the resonance region.

The analogy of gluons to photons is fruitful but colour polarizability asks for further investigation. The hadronic index of refraction can, in principle, be determined from the gluon polarization operator in the strong gluon field which is unknown yet. The role of the finite size of the nuclear medium was considered in [2]. The parameter defining the notion of finiteness was formulated. It is important for small indices of the refraction. The energy dependence of parton density must be studied in experiment. Search for Cherenkov gluons in other hadronic reactions (see [16, 17]) is necessary.

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References

[1] Dremin I M 1979 *JETP Lett* **30** 140

[2] Dremin I M 1981 *Sov J Nucl Phys* **33** 726

[3] Dremin I M 2006 *Nucl Phys* A **767** 233

[4] Majumder A and Wang X N 2006 *Phys Rev* C **73** 051901

[5] Koch V, Majumder A and Wang X N 2006 *Phys Rev Lett* **96** 172302

[6] Adams J *et al* (STAR) 2005 *Phys Rev Lett* **95** 152301

[7] Adler S S *et al* (PHENIX) 2006 *Phys Rev Lett* **97** 052301

[8] Ulery J G (STAR) 2006 nucl-ex/0609047; Pruneau C A (STAR) 2007 *J Phys* G (with *Proceedings QM2006* Shanghai China)

[9] Zhang C (PHENIX) 2007 *J Phys* G (with *Proceedings QM2006* Shanghai China)

[10] Dremin I M 2006 hep-ph/0602135.

[11] Goldberger M and Watson K 1964 *Collision Theory* (John Wiley and Sons Inc) Ch 11 sect 3 sect 4

[12] Feynman R P, Leighton R B and Sands M 1963 *The Feynman Lectures in Physics* (Addison-Wesley PC Inc) vol 3 ch 31 and v 7 ch 32

[13] Dremin I M 2007 *Int J Mod Phys* E (with *Proceedings IWCF2006* Hangzhou China)

[14] Dremin I M and Nazirov M T 1989 *Yadernaya Fizika* **49** 1695

[15] Block M M 2006 *Phys Rep* **436** 71

[16] Apanasenko A V *et al* 1979 *JETP Lett* **30** 145

[17] Agababyan N M *et al* (NA22) 1996 *Phys Lett* B **389** 397

[18] Dremin I M, Sarycheva L I and Teplov K Yu 2006 *Eur Phys J* C **46** 429

[19] Satarov L M, Stoecker H and Mishustin I N 2005 *Phys Lett* B **627** 64